8922-EN-01
DTIC.

NSF CONTRACT No. N-68171-99-M-6643 15/09/99 - 14/09/00

CONTRACTOR/P.I. Prof. Peter Wadhams
Scott Polar Research Institute,
University of Cambridge,
Lensfield Road, Cambridge, CB2 1ER, UK

TITLE: Further analysis of UK submarine sonar data for comparison with similar US datasets

STAGE: Final Report

ABSTRACT: The first phase of this process was the comparison of statistical parameters from analyses carried out by degree of latitude, cognisant of the summer collection period of the 1996 cruise. The second phase was a closer examination of instrument differences and how these might influence current selection criteria in statistical analysis. The final phase has been the consolidation of further data from 1976 and 1991 to permit the comparison of the 1996 dataset with earlier data from similar data collection areas in the same season.

REPORT

With the funding provided by this NSF contract three years of submarine cruise data have been analysed in order to determine sea ice thickness as measured using upward looking sonar instruments deployed on UK submarines in the Arctic. Digitising and analysing upward looking sonar data is a time consuming activity as data, recorded on paper rolls, need to be digitised and combined with time and navigation data which is rarely complete or easily accessible. The years that have been analysed are 1976, 1991 and 1996. The 1991 data has been made publicly available, via the NSIDC web site, and the other two years should follow shortly. The year 1992, originally intended for analysis, has not been analysed due to a lack of available navigational data needed to correctly establish positions for that cruise. In addition the years 1979 and 1990 have been digitised and are awaiting further analysis.

In conjunction with the digitalisation and analysis of these data, a comparison between 780 and 2077 sonar systems has also been carried out for the year 1996 (see 6 monthly interim report). These two systems use differing beam widths and recording methods. Results from this comparison indicate little difference between the two sonar systems. Mean ice thickness does not appear to be strongly affected by the instrument used; however other properties, such as lead widths and spacing as well as rough ice detection, do give slightly different results.

A comparison between sea ice thickness in the years 1976 and 1996 has been made (Wadhams and Davis, 2000) which indicates a 43% thinning of the sea ice in the region observed by the two submarine cruises. This agrees with the results from Rothrock et al. (1999) who found a 42% average decrease in sea ice thickness using US submarine data. In addition various sea ice parameters such as mean draft, percentage open water and ridge frequency have been studied and their relationships determined for the 1996 cruise (Wadhams and Davis, 2001). This will enable

parameterisations to be developed that relate satellite observable parameters, such as percentage open water, to mean draft and ridge distribution.

FUTURE WORK

A number of cruises are yet to be digitised and/or analysed. We are currently liasing with the UK Hydrographic Office and the Naval Oceanographic Office for additional time/positional information to complete the header information for the 1992 NSIDC database as well as negotiating for the release of a substantial 1988 dataset collected in joint exercise with the US Navy in August/September of that year. Work will continue on the 1978 and 1990 data sets.

The comparison of a number of digitising methods has shown that the determination of sea level, essential to the correct analysis of 780 draft data, is sensitive to techniques and interpretation. With the acquisition of a new digital scanner for the reading of paper rolls, on which 780 data is recorded, it is hoped that future analysis will be improved.

PUBLICATIONS

Two peer reviewed articles have been published based on the work funded by this NSF contract. Abstracts from these two articles are included here and reprints are attached with this report.

"Further evidence of ice thinning in the Arctic Ocean"
(Wadhams and Davis, 2000)

A sea-ice thickness profile obtained in September 1996 from the Eurasian Basin of the Arctic Ocean between Fram Strait and the North Pole, was compared with a profile obtained in the same region in September-October 1976. A decline in mean ice draft of 43.2% was observed over the 20-year interval, in agreement with changes observed in other parts of the Arctic Ocean by Rothrock et al. (1999).

"Arctic sea ice morphological characteristics in summer 1996"
(Wadhams and Davis, 2001).

A sea-ice thickness profile obtained in September 1996 from the Greenland Sea and Eurasian Basin, extending as far as the North Pole, has shown an unusually open ice cover with low mean drafts, large amounts of open water and little deep pressure ridging. Comparisons with data obtained from the same region in October 1976 show that mean ice draft has declined by 43% and that the decline can largely be ascribed to a loss of the thickest ice.

OBITUARY

The chief researcher carrying out the analysis, Norman Davis, fell ill in the final phase of this project and passed away in May 2001.

REFERENCES

Rothrock, D.A., Yu, Y. & Maykut, G.A. Thinning of the Arctic sea-ice cover. *Geophys. Res. Letters,* **26**, 3469-3472 (1999).

Wadhams, P. & Davis, N.R. Further evidence of ice thinning in the Arctic Ocean. *Geophys.Res.Letters,* **27**, 3973-3975, (2000).

Wadhams, P. & Davis, N.R. Arctic sea ice morphological characteristics in summer 1996. *Ann. Glaciol.,* **33**, 165-170, (2001).

Annals of Glaciology 33 2001

Arctic sea-ice morphological characteristics in summer 1996

P. Wadhams, N. R. Davis†
Scott Polar Research Institute, University of Cambridge, Lensfield Road, Cambridge CB2 1ER, England

ABSTRACT. A sea-ice thickness profile obtained in September 1996 from the Greenland Sea and the Eurasian Basin, extending as far as the North Pole, has shown an unusually open ice cover with low mean drafts, large amounts of open water and little deep pressure ridging. Comparisons with data obtained from the same region in October 1976 show that mean ice draft has declined by 43% and that the decline can largely be ascribed to a loss of the thickest ice.

INTRODUCTION

During September 1996 one of us (P.W.) took part in an Arctic operational voyage by HMS *Trafalgar* during which upward sonar profiling of the ice canopy was carried out, together with sidescan sonar profiling and along-track temperature, salinity and fluorescence monitoring. We here report on the ice-draft characteristics revealed by the upward-looking sonar, of which two systems were in simultaneous use. The first was an Admiralty-pattern 780 system, recording on paper chart; this was identical to the system used by HMS *Superb* in May 1987 (Wadhams, 1992), and on other UK submarine voyages of the 1980s and early 1990s from which data have recently been released but not yet analyzed. The second was a new narrow-beam digital system, the 2077, which is better at resolving the structure of individual pressure-ridge keels. In a future paper we will report on comparisons between the two systems; in the present paper we report on results obtained from the 2077 only.

In October 1976 a voyage to the same part of the Arctic was carried out by HMS *Sovereign*, and similar datasets collected (Wadhams, 1981). Since the seasons were almost identical, we compare results from the two cruises in order to test whether the thinning observed over a similar time lapse by Rothrock and others (1999) in other parts of the Arctic is applicable also to the region between Fram Strait and the North Pole.

DATA ANALYSIS

An advantage of the 2077 system is that it is coupled to the boat's inertial navigation system, so that data are recorded directly as draft vs horizontal distance. This avoids one of the most time-consuming tasks with the 780 sonar, which is the need to combine the draft–time profile record with the boat's navigation to yield a draft–distance relationship. In addition, the 2077 automatically removes submarine depth variations so as to yield a continuous sea-level profile which is subtracted from the measured range to the ice bottom so as to yield a draft. However, accurate depth removal was dependent upon knowing the vertical sound velocity profile between the boat and the sea surface. This profile, based on periodic XSV (expendable sound velocity) casts, could only be updated at intervals, and so an error in range, and hence in inferred draft, could develop. Fortunately, the summer ice cover was remarkably open, and contained many unfrozen leads (identified via the upward TV camera record and from the high sonic reflection coefficient of open water). These provided frequent zero references through which the zero error could be removed. Corrected drafts were then grouped in 50 km data lengths, and statistics were generated.

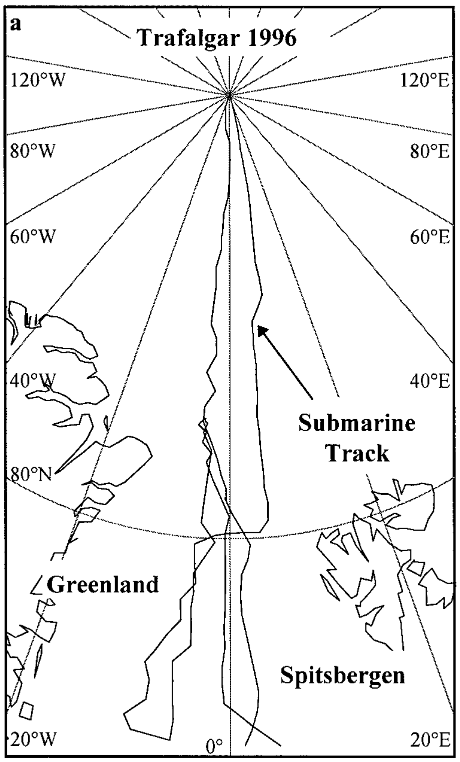
Figure 1 shows schematically the track of the submarine. The track within the Eurasian Basin north of Fram Strait comprised a "westerly" leg at about 5° W and an "easterly" leg at about 5° E. These were analyzed separately to test for zonal variations in mean ice thickness. Within the Greenland Sea the track can again be divided into a westerly leg which followed the core of the East Greenland Current over the shelf break, sampling typical ice conditions for each latitude, and an easterly leg which lay more within the marginal ice zone (MIZ).

MEAN ICE DRAFT

The dataset with which the 1996 profiles are compared was obtained in September–October 1976 by HMS *Sovereign* (Wadhams, 1981). Figure 1b shows *Sovereign*'s track alongside that of *Trafalgar*. *Sovereign* was equipped with a sonar system which had a narrow beamwidth in the athwartships direction but a wider beam fore-and-aft. A correction for beamwidth effects was applied to the data (Wadhams, 1981) by applying a calibration based on convolving a genuinely narrow-beam ice profile (that of USS *Gurnard*, 1976) with a sonar beam of width equal to that aboard *Sovereign*, then examining the percentage change in mean draft occurring in different ice regimes. We can therefore legitimately compare the *Sovereign* data (beamwidth-corrected) with the *Trafalgar* data (not beamwidth-corrected, but obtained by a narrow-beam instrument).

The protocol of track selection was to compare those portions of the tracks of the two submarines which lay in 1° latitude increments and within the longitude limits 5° W to 5° E. This involved a total of about 2100 km of track from each submarine, and corresponds as closely as possible to

† Deceased.



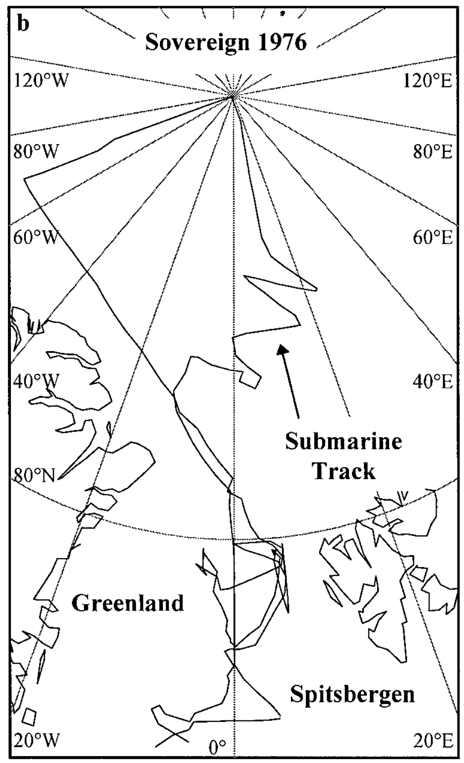


Fig. 1. Schematic diagram of submarine tracks, (a) September 1996, (b) October 1976.

Rothrock and others' (1999) concept of "crossing tracks". The resulting mean ice drafts are as shown in Table 1.

The overall decline in mean ice draft between 1976 and 1996, giving equal weight to each latitude range between 81° N and 90° N, is 43.2%, which is close to the value found by Rothrock and others (1999) for the Arctic basin as a whole. We note that Rothrock and others' track comparisons occur over the North Pole region and Canada Basin, with few in the Eurasian Arctic and none south of 84° N in the Eurasian Basin. These results therefore both support the U.S. findings and extend them to a part of the Arctic not covered by U.S. datasets.

There was a seasonal displacement of, on average, 4 weeks between the 1976 and 1996 experiments. Rothrock and others (1999) "standardized" their datasets, obtained during various periods of the summer between July and October, to 15 September by the use of a sea-ice model. If we tentatively use the same seasonal cycle as shown in Rothrock and others (1999), a small seasonality correction gives us a decline of 41% rather than 43.2%, still in good agreement with the U.S. results.

Table 1. Mean ice drafts in 1° latitude bins spanning Greenwich meridian, from September 1996 Trafalgar *cruise and September–October 1976* Sovereign *cruise*

Latitude range	*Mean draft*		*1996 as % of 1976*
	1996	*1976*	
°N	m	m	
81–82	1.57	5.84	26.9
82–83	2.15	5.87	36.6
83–84	2.88	4.90	58.7
84–85	3.09	4.64	66.6
85–86	3.54	4.57	77.4
86–87	3.64	4.64	78.5
87–88	2.36	4.60	51.2
88–89	3.24	4.41	73.4
89–90	2.19	3.94	55.5
Overall	**2.74**	**4.82**	**56.8**

ICE-DRAFT DISTRIBUTIONS

Figure 2 shows four examples of histograms of the draft distribution of the westerly track of the 1996 cruise, plotted to a maximum draft of 10 m. In each case a characteristic of the distributions is the large fraction of open water and thin ice (first band in histogram; <10 cm deep), even in the 89–90° N example. The Greenland Sea histogram consists mainly of thin ice, with a low mean draft (Table 2) and no peak characteristic of typical Arctic first- or multi-year thicknesses. The Fram Strait example also contains much young ice, but there is a peak at 2.5 m draft which is typical of melting multi-year ice. The examples within the Eurasian Basin show a peak at about 2.5 m, together with increasing amounts of deeper, ridged ice. However, as compared to earlier thickness distributions from the late-summer or autumn period (e.g. HMS *Sovereign* data from October 1976, shown in Wadhams, 1981), these distributions show very much reduced amounts of thicker ice. The mean ice drafts in Table 2 differ slightly from those in Table 1, which contains only those track sections which lay between 5° W and 5° E.

The 1° binned ice-draft distributions are shown plotted against latitude for both tracks (Fig. 3) where the data are displayed for total, level and rough ice, and the decline in open water/thin ice with increasing latitude is clearly illustrated. Level ice is defined by a simple slope criterion. In both cases the continuing high incidence of open water and very thin ice at all latitudes is apparent, while the level-ice plots (particu-

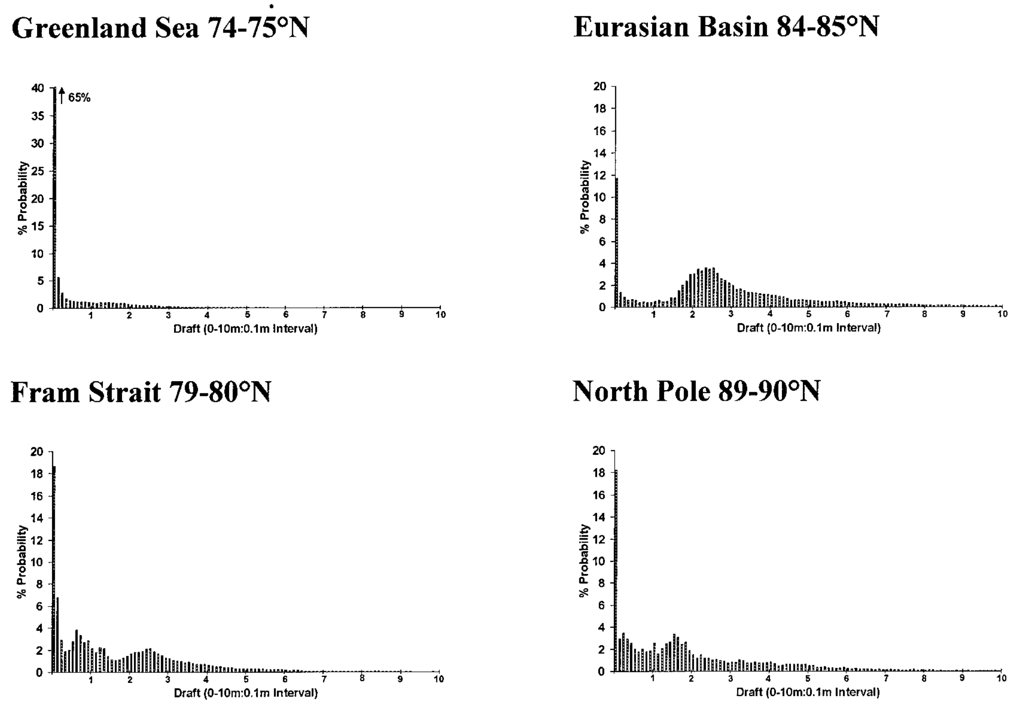


Fig. 2. Probability density functions of ice draft from four regions of the 1996 cruise.

Table 2. Statistical parameters derived from data in 1° latitude bins, 1996 cruise

		Draft		*Leads*			*Ridges*	
Lat.	*Mean*	*Std dev.*	*% level*	*% OW*	*No/100 km*	*No/100 km > 5*	*Mn dft > 5*	*Std dev. > 5*
(a) Westerly track								
73–74	0.52	0.23	28.8	11.3	607	0	0	0
74–75	0.49	1.07	73.6	75.4	383	30	6.67	1.62
75–76	0.59	1.31	69.8	72.8	423	35	7.58	2.96
76–77	0.65	1.27	68.1	58.1	472	62	8.01	2.15
78–79	1.60	1.82	34.7	6.4	286	98	8.85	3.43
79–80	1.67	1.76	56.5	27.9	164	139	6.73	1.59
80–81	0.96	1.62	49.6	46.1	404	106	7.53	2.58
81–82	1.54	1.88	54.8	29.5	226	166	7.40	2.19
82–83	2.12	2.56	50.4	32.0	135	269	7.97	2.86
84–85	3.09	2.50	35.0	13.5	125	421	7.82	2.63
85–86	3.54	2.56	25.8	7.6	101	514	7.87	2.72
86–87	3.64	2.24	24.4	2.6	61.1	601	7.49	2.04
87–88	2.36	1.79	28.9	4.5	50	220	7.61	2.24
88–89	3.24	2.26	25.9	6.3	71	524	7.37	2.07
89–90	2.00	2.18	31.6	22.0	463	307	7.16	3.39
(b) Easterly track								
71–72	0.78	0.77	40.7	32.7	654	0	0	0
72–73	0.58	0.55	44.4	22.7	544	10	10.59	0.71
73–74	0.53	0.48	37.0	28.8	769	9	5.59	0.59
74–75	1.02	0.66	27.4	11.9	388	9	6.24	0.89
75–76	1.20	0.37	21.7	0.3	23	0	0	0
76–77	0.72	0.68	58.2	27.7	886	0	8.85	4.70
77–78	0.32	0.21	64.2	51.9	1443	0	0	0
78–79	0.37	0.22	61.0	43.6	1437	0	0	0
79–80	1.32	1.87	53.2	37.1	419	138	7.76	2.70
80–81	2.20	2.12	30.6	17.4	321	247	7.24	2.17
81–82	2.05	1.68	24.7	12.9	280	263	6.41	1.63
83–84	2.76	2.16	28.3	1.6	58	305	7.55	2.35
85–86	2.80	1.78	28.2	3.8	53	304	7.25	1.80
89–90	1.98	1.82	37.1	22.7	295	256	6.88	1.75

Notes: OW, open water; No/100 km, number per 100 km; No/100 km > 5, number per 100 km greater than 5 m; Mn dft > 5, mean draft greater than 5 m.

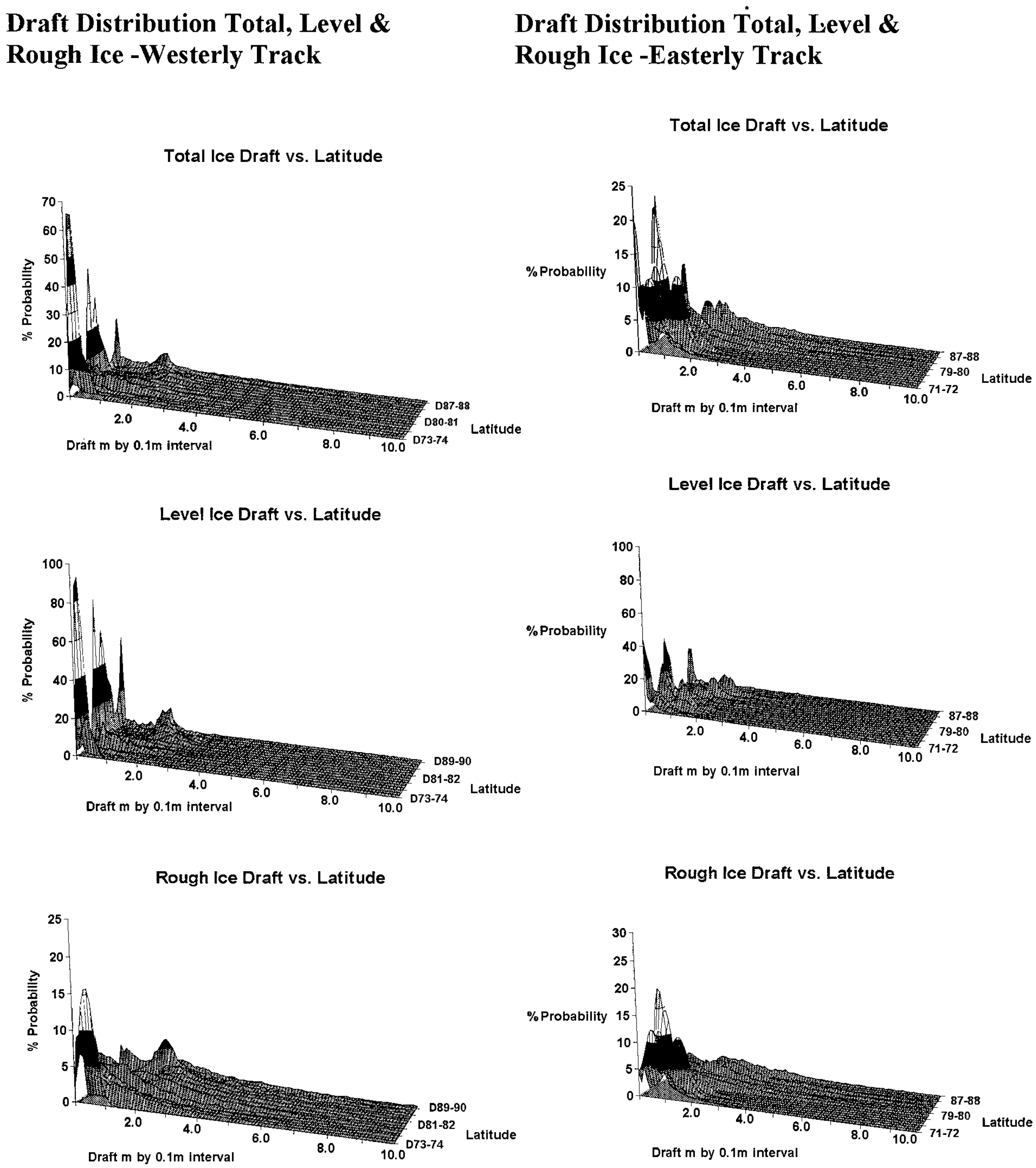


Fig. 3. Probability density functions of 1996 ice draft in 1° bins plotted against latitude for westerly and easterly tracks. Top: all ice; middle: level ice only; bottom: rough ice only.

larly the easterly track) show a radical drop in the draft of the main peak south of Fram Strait (80° N), indicating rapid melt within the Greenland Sea. The rough-ice plots show a similar transition at about the same latitude, with the thick ice in the 5–10 m draft range almost disappearing.

PRESSURE RIDGES AND LEADS

Table 2 shows statistics for pressure-ridge and lead occurrences for the westerly and easterly tracks in 1° bins. A missing bin implies that <50 km of track data were available within that degree increment. Independent ridges were defined in the same way as for previous analyses (Wadhams, 1981, 1992), with a minimum draft value of 5 m. Leads were defined as features at least 5 m wide containing ice of draft <30 cm. It can be seen that there is a radical drop in ridge frequency south of Fram Strait, while lead occurrence is more variable. The ridging variation can be seen more clearly by considering the volume of ridged ice per unit length of track. This should be proportional to nh^2, where n is the number of ridges per unit track length and h is the mean draft, on the assumption that ridges of all depths have the same average shape factor (ratio of cross-sectional area to square of draft).

Figure 4 (drawn from westerly track data) shows that, with track length expressed in km and ridge draft in m, the relative volume increases from 13 at 74° N to 130–340 in the zone north of Fram Strait. The most rapid change occurs within and just north of the Strait, in the region 80–82° N. The percentage of surface occupied by leads ranges from 72–

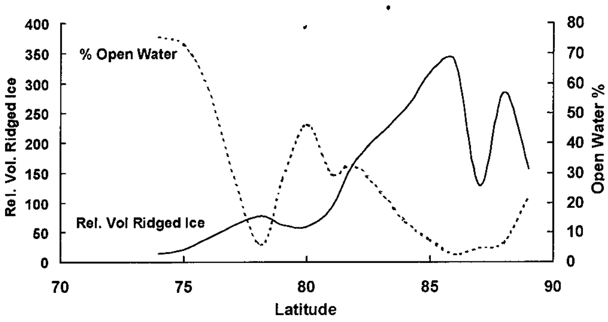


Fig. 4. Percentage of open water, and relative volume of ridged ice (expressed as nh^2, where n is number of ridges per km, and h is ridge draft in m), as functions of latitude.

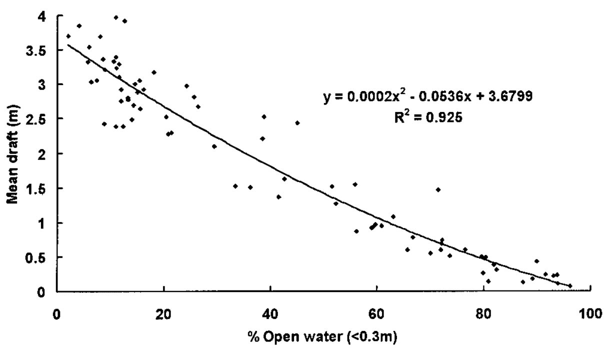


Fig. 5. Mean draft of a 50 km section of track plotted against percentage open water in the section.

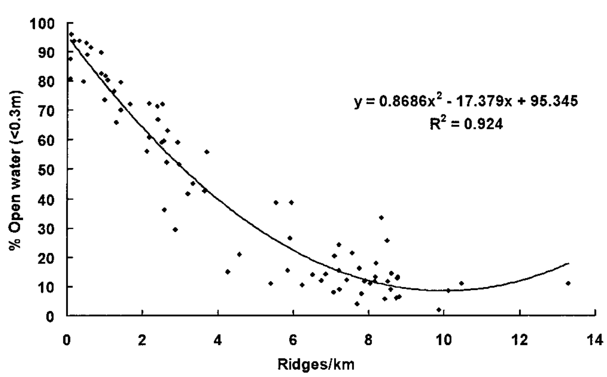


Fig. 6. Percentage open water plotted against number of ridges per km, in 50 km track sections.

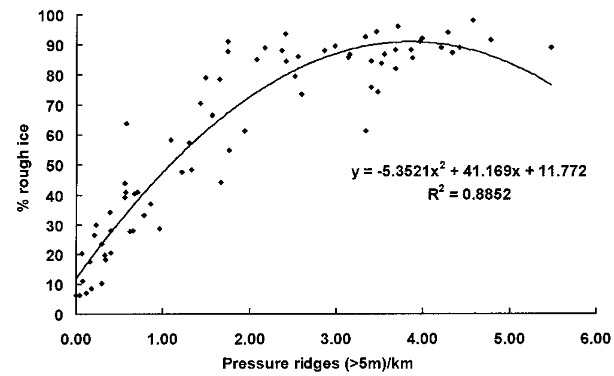


Fig. 7. Percentage of rough ice in a 50 km section plotted against number of pressure ridges deeper than 5 m per km of track.

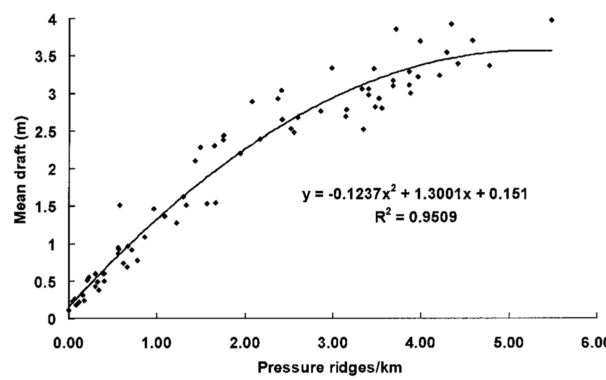


Fig. 8. Mean draft of a 50 km section plotted against number of pressure ridges deeper than 5 m per km of track.

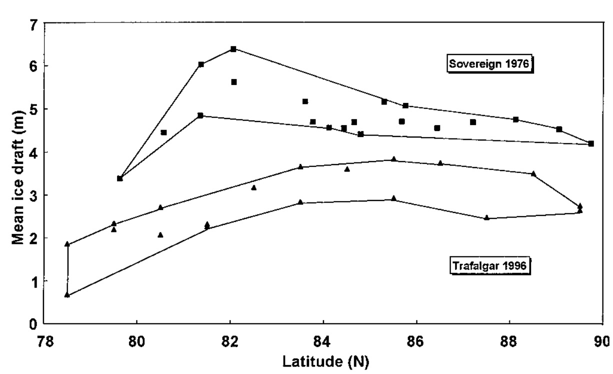


Fig. 9. Mean drafts for ice deeper than 0.5 m from 1976 and 1996 data, between 78° N and North Pole in region 10° W to 10° E.

75% in the lower latitudes, to 28–46% within Fram Strait and lower values of < 10% near the Pole, with an increase to 22% at the Pole itself. The large variability is a statistical one, due to the open water and young ice being contained within a limited number of leads; the question of the statistical variability of parameters extracted from finite lengths of track has been examined by Wadhams (1997), who found that open-water fraction has a much higher variability than ridge frequencies.

PARAMETER RELATIONSHIPS

Relationships between statistical quantities were explored, to investigate likely interactions which might allow the ice morphology to be parameterized, or related to quantities detectable by satellite. The percentage of open water, a quantity that can be derived from passive-microwave or observed from visible-band sensors, was, as expected, negatively correlated with mean draft (Fig. 5). Davis and Wadhams (1995) found that the frequency of pressure ridges was lower in ice regimes with large amounts of open water, and this was also observed here (Fig. 6). The fraction of rough ice, which is mainly ice that has undergone deformation processes (although some undeformed multi-year ice might be rough enough to be counted), might also be expected to be related to the occurrence of pressure ridges, and this is also repeated here (Fig. 7). The other strongly suggested relationship is shown when correlating pressure-ridge occurrence with the overall mean ice draft (Fig. 8). Note that the relationship becomes less strong with high mean ice drafts.

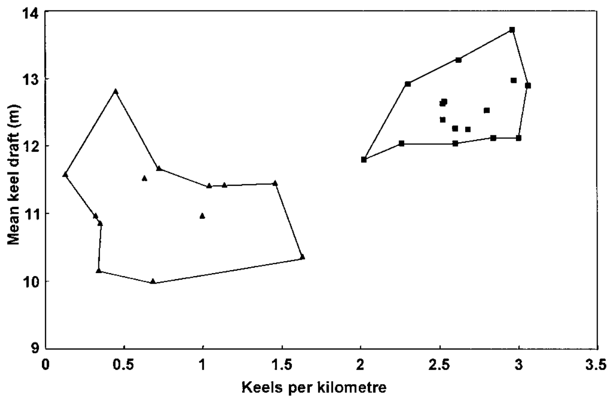


Fig. 10. Ridges deeper than 9 m: a plot of mean keel draft against mean number of ridges per km for data from 1976 and 1996 between 81° N and the North Pole.

DEPLETION OF THICK ICE AND DEEP RIDGES

The statistics presented so far indicate clearly that the ice cover in 1996 was very open, with much thin ice and open water present, and with a relative absence of very thick ice. A comparison with the 1976 *Sovereign* data enables us to see more clearly the magnitude of the thick-ice depletion. The first question that we can answer is, to what extent can the decline in mean ice thickness shown in Table 1 be ascribed purely to the more open nature of the ice cover? If all the ice not in leads were pushed up together, would the mean thickness still be less? The answer is resoundingly positive. Figure 9 shows the results of calculating the mean thickness of all ice thicker than 0.5 m for 1976 (100 km sections in the range 10° W to 10° E) and 1996 (1° sections from easterly and westerly tracks) using data from north of 78° N. There is still a very substantial decline in mean thickness in 1996.

The second question is, what contribution to the thinning is made by a loss of very thick ice? Very thick ice is all contained in pressure ridges, so we can examine the comparative statistics for all pressure ridges deeper than 9 m for 1976 and 1996. Figure 10 shows a plot of ridge numbers per km of track against mean ridge draft for ridges deeper than 9 m found in 1976 and 1996 (data north of 81° N as for Fig. 9). The loss of pressure ridges is startling. There is no overlap between the envelope of the 1976 and 1996 results, i.e. there is no part of the region where there was as much ridging in 1996 as in 1976. On average, in this region of the Arctic, there were only a quarter as many deep ridges in 1996 as in 1976. It is clear that one of the most important aspects of the Arctic ice cover in its newly reduced state is that deep pressure ridges are now almost absent.

CONCLUSIONS

This cruise has provided a contemporary snapshot view of summer ice conditions in the Eurasian Basin and Greenland Sea. A remarkable loss of ice thickness is observed relative to older summer data. As compared to data from the *Sovereign* cruise of October 1976, the mean thickness over the latitude range 81–90° N is reduced by 43%, in agreement with summer data from other parts of the Arctic basin reported by Rothrock and others (1999). The thinning reveals itself through larger amounts of open water, a low mean draft of undeformed ice and a shortage of deep pressure ridges. Of these changes, the significant decline in the occurrence of pressure ridges represents a major change in the morphology of Arctic sea ice.

ACKNOWLEDGEMENTS

We are grateful to the U.K. Ministry of Defence (Navy) for the release of data; to Flag Officer Submarines for the opportunity to take part in the voyages concerned; to the Commanding Officer and crew of HMS *Trafalgar*; and for financial support to the U.K. Natural Environment Research Council and the U.S. National Science Foundation.

REFERENCES

Davis, N. R. and P. Wadhams. 1995. A statistical analysis of Arctic pressure ridge morphology. *J. Geophys. Res.*, **100**(C6), 10,915–10,925.

Rothrock, D. A., Y. Yu and G. A. Maykut. 1999. Thinning of the Arctic sea-ice cover. *Geophys. Res. Lett.*, **26**(23), 3469–3472.

Wadhams, P. 1981. Sea-ice topography of the Arctic Ocean in the region 70° W to 25° E. *Philos. Trans. R. Soc. London, Ser. A*, **302**(1464), 45–85.

Wadhams, P. 1992. Sea ice thickness distribution in the Greenland Sea and Eurasian Basin. *J. Geophys. Res.*, **97**(C4), 5331–5348.

Wadhams, P. 1997. Ice thickness in the Arctic Ocean: the statistical reliability of experimental data. *J. Geophys. Res.*, **102**(C13), 27,951–27,959

Further evidence of ice thinning in the Arctic Ocean

Peter Wadhams and Norman R. Davis

Reprinted from
Geophysical
Research
Letters
Volume 27, Number 24, December 15, 2000

GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 24, PAGES 3973-3975, DECEMBER 15, 2000

Further evidence of ice thinning in the Arctic Ocean

Peter Wadhams and Norman R. Davis

Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK

Abstract. A sea ice thickness profile, obtained in September 1996 from the Eurasian Basin of the Arctic Ocean between Fram Strait and the North Pole, was compared with a profile obtained in the same region in September-October 1976. A decline in mean ice draft of 43% was observed over the 20-year interval, in agreement with changes observed in other parts of the Arctic Ocean by *Rothrock et al.* [1999].

1. Introduction

Our knowledge of the regional and temporal variability of sea ice thickness in the Arctic comes mainly from the results of upward sonar profiling by submarines. Data have been collected by US submarines since 1958 and by British submarines since 1971, usually on an opportunity basis during military operations. More recently the US SCICEX program (1993-9) has enabled annual data gathering to take place by civilian scientists, mainly in the Canada Basin. *Rothrock et al.* [1999] have reported on a comparison between data obtained on this program during the late summers of 1993, 1996 and 1997, and data obtained from six summer operations during the period 1958-1976. Twenty-nine crossing places were identified, where a submarine track from the recent period crossed one from the early period, and the corresponding tracks (of average length 160 km) were compared in mean thickness. After an adjustment to a standard date of September 15, it was found that for every region of the Arctic there was a decline in mean draft, with the most modest declines in the Beaufort Sea and greater losses in the North Pole region and Nansen Basin. The overall change in mean draft was from 3.1 m in the early period to 1.8 m in the recent period, a decline of 42%.

We here present results from a British submarine cruise carried out in the Eurasian Basin in September of 1996, in which it followed a track which was very close to that of an earlier British submarine cruise in September-October 1976. Comparison of the two datasets over the latitude range 81-90°N in the longitude slot 5°E to 5°W shows a mean loss of mean draft of 43.2%, in close agreement with the results of *Rothrock et al.* and extending them to a part of the Arctic not covered by the US datasets.

2. The data

The 1996 voyage was undertaken by *HMS Trafalgar* and one of us (PW) carried out the data collection on board. Figure 1b is a schematic view of the track of the submarine, which involved data gathering in the Greenland Sea as well as the Arctic Basin. Results on statistical distributions of ice thickness, ridge drafts and lead spacings from the whole cruise are reported by *Wadhams and Davis* [2000].

Paper number 2000GL011802.
0094-8276/00/2000GL011802$05.00

Ice draft data were collected by two upward-looking sonar systems. The first was an Admiralty-pattern 780 system, recording on paper chart; this was identical to the system used by *HMS Superb* in May 1987 [*Wadhams*, 1992], and on other UK submarine voyages of the 1980s and early 1990s from which data have recently been released but not yet analyzed. The second was a new narrow-beam digital system called 2077 which is better at resolving the structure of individual pressure ridge keels. Comparisons between the two systems, in particular a test of beamwidth based on the shape of the underside power spectrum [*Wadhams and Davis*, 1994], shows that the 2077 had an effective surface beam diameter of less than 5 m. We therefore report on data obtained by the 2077 system, noting that it can be compared only with data from other cruises which used a narrow-beam sonar or where a correction for sonar beamwidth has been applied. An advantage of the 2077 system is that it is coupled to the boat's inertial navigation system, so that data are recorded directly as draft versus horizontal distance, avoiding the need to combine a draft-time profile record with the boat's navigation to yield a draft-distance relationship. In addition, the 2077 automatically removes submarine depth variations so as to yield a continuous sea level profile which is subtracted from the measured range to the ice bottom so as to yield a draft. However, the depth removal is dependent upon knowing the vertical sound velocity profile between the boat and the sea surface. This profile, based on periodic XSV (expendable sound velocity) casts, could only be updated at intervals, and so a range error to the open water surface could develop. Fortunately, the summer ice cover was remarkably open, and contained many unfrozen leads (identified via the upward TV camera record and from the high sonic reflection coefficient of open water). These provided frequent zero references through which the range error could be removed.

The dataset with which the 1996 profiles are compared was obtained in September-October 1976 by *HMS Sovereign* [*Wadhams*, 1981]. Fig. 1a shows *Sovereign's* track alongside that of *Trafalgar* (Fig. 1b). *Sovereign* was equipped with a sonar system which had a narrow beamwidth in the athwartships direction but a wider beam fore-and-aft. A correction for beamwidth effects was applied to the data [*Wadhams*, 1981] by applying a calibration based on convolving a genuinely narrow-beam ice profile (that of *USS Gurnard*, 1976) with a sonar beam of width equal to that aboard *Sovereign*, then examining the percentage change in mean draft occurring in different ice regimes. We can therefore legitimately compare the *Sovereign* data (beamwidth-corrected) with the *Trafalgar* data (not beamwidth corrected, but obtained by a narrow-beam instrument).

3. Changes in mean ice draft

The protocol of track selection was to compare those portions of the tracks of the two submarines which lay in 1° latitude increments and within the longitude limits 5°W to 5°E. This involved a total of about 2100 km of track from

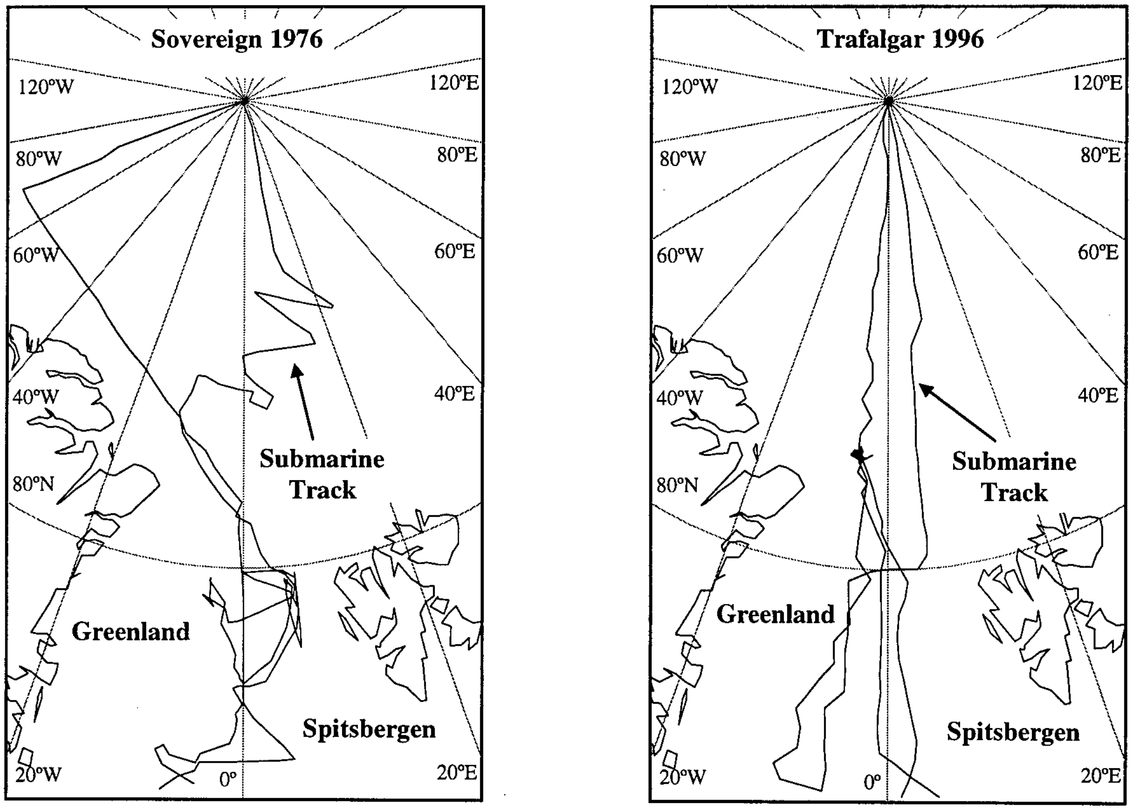


Figure 1. Tracks within Arctic Basin of (a) *HMS Sovereign*, 1976, and (b) *HMS Trafalgar*, 1996.

each submarine, and corresponds as closely as possible to *Rothrock et al.'s* concept of "crossing tracks". The resulting mean ice drafts are shown in Table 1.

The overall decline in mean ice draft between 1976 and 1996, giving equal weight to each latitude range between 81°N and 90°N, is 43.2%, which is close to the value found by *Rothrock et al.* [1999] for the Arctic Basin as a whole. We note that *Rothrock et al.'s* track comparisons occur over the North Pole region and Canada Basin, with few in the Eurasian Arctic and none south of 84°N in the Eurasian Basin. These results therefore both support the US findings and extend them to a part of the Arctic not covered by US datasets.

There was a seasonal displacement of, on average, four weeks, between the 1976 and 1996 experiments. *Rothrock et al.* "standardized" their datasets, obtained during various periods of the summer between July and October, to September 15 by the use of a sea ice model. If we tentatively

Table 1. Mean ice drafts in 1° latitude bins spanning Greenwich meridian, from September 1996 *Trafalgar* cruise and September-October 1976 *Sovereign* cruise.

Latitude Range	Mean draft (meters)		1996 as %
	1996	1976	of 1976
81-82°	1.57	5.84	26.9
82-83°	2.15	5.87	36.6
83-84°	2.88	4.9	58.7
84-85°	3.09	4.64	66.6
85-86°	3.54	4.57	77.4
86-87°	3.64	4.64	78.5
87-88°	2.36	4.6	51.2
88-89°	3.24	4.41	73.4
89-90°	2.19	3.94	55.5
Overall	2.74	4.82	56.8

use the same seasonal cycle as shown in the *Rothrock et al.* paper, a small seasonality correction gives us a decline of 41% rather than 43.2%, still in good agreement with the US results.

The detection of ice thinning in the sector of the Eurasian Basin between Fram Strait and the North Pole was first reported in 1990 by Wadhams, who found a 15% decrease in mean draft over a 300, 000 sq km area between September-October 1976 (the *Sovereign* dataset) and May 1987 (*HMS Superb*). The main contribution to the loss of volume appeared to be the replacement of multi-year and ridged ice by young and first-year ice. We note that this loss of ice thickness, although at the time it appeared large, was actually an underestimate of the thinning which must have taken place between 1976 and 1987 because of (a) the seasonality factor, in that the more recent experiment was conducted in winter, and (b) the fact that the *Superb* profiles were obtained by a sonar of finite beamwidth and that a beamwidth correction was applied to the earlier but not the later data. We do not feel that it is valid to make a model-based seasonality correction between winter and summer, as *Rothrock et al.* did between two parts of the summer, since the thickness changes involved would be too large. However, comparing our present results with those reported by *Wadhams* [1990], we speculate that a substantial part of the thinning that occurred in the experimental region between 1976 and 1996 took place during the first of those two decades.

Given the very rapid changes which are occurring in the ocean structure of the Arctic, with a greater influx of heat into the Atlantic layer and a retreat of the cold halocline [*Steele and Boyd*, 1998], and the significant retreat in ice extent which is also being observed accompanied by a decline in multi-year ice concentration [*Johannessen et al.*, 1999], we

feel that this additional support for the dramatic thinning rates reported by *Rothrock et al.* has serious implications for the future of high-latitude climates.

Acknowledgments. We are grateful to the Ministry of Defence (Navy) for the release of data; to Flag Officer Submarines for the opportunity to take part in the voyages concerned; to the Commanding Officer and crew of *HMS Trafalgar*; and for financial support to the Natural Environment Research Council and the National Science Foundation.

References

Johannessen, O.M., Shalina, E.V. and Miles, M.W., Satellite evidence for an Arctic sea ice cover in transformation, *Science*, 286, 1937-1939, 1999.

Rothrock, D.A., Yu, Y. and Maykut, G.A., Thinning of the Arctic sea-ice cover, *Geophys. Res. Letters*, 26, 3469-3472, 1999.

Steele, M. and Boyd, T., Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, 103(C5), 10419-10435, 1998.

Wadhams, P., Sea-ice topography of the Arctic Ocean in the region 70°W to 25°E, *Phil. Trans. Roy. Soc., Lond.*, A302, 45-85, 1981.

Wadhams, P., Evidence for thinning of the Arctic ice cover north of Greenland, *Nature*, 345, 795-797, 1990.

Wadhams, P., Sea ice thickness distribution in the Greenland Sea and Eurasian Basin, May 1987, *J. Geophys. Res.*, 97, 5331-5348, 1992.

Wadhams, P. and Davis, N.R., The fractal properties of the underside of Arctic sea ice, in *Marine, Offshore and Ice Technology*, edited by T.K.S. Murthy, P.A. Wilson and P. Wadhams, Fifth International Conference on Computer Aided Design, Manufacture and Operation in the Marine and Offshore Industries, Incorporating the Fourth Ice Technology Workshop, Computational Mechanics Publications, Southampton, 1994.

Wadhams, P. and Davis, N.R., Arctic sea ice morphological characteristics in summer 1996, *Ann. Glaciol.*, 33, in press, 2000.

(Received May 19, 2000; accepted October 13, 2000.)